Planetary and satellite atmospheres in the far infrared range: Results and challenges

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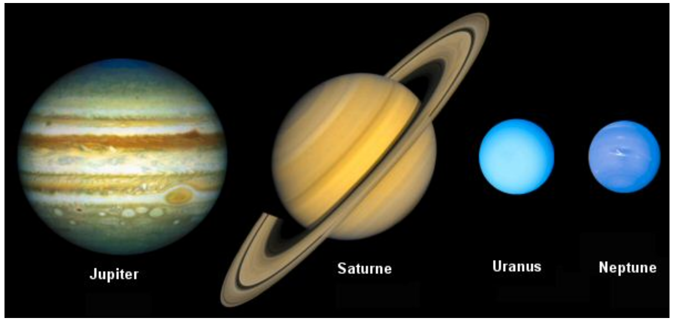
Key questions about the outer solar system formation and evolution (1)

How did the giants planets form and can we trace their migration?

- Elemental and isotopic ratios
  - H_2/He, D/H in HD, $^{15}N/^{14}N$ in NH_3, $^{13}C/^{12}C$ & $^{15}N/^{14}N$ in CO & HCN
- Disequilibrium species (CO, PH_3, HCN)
- > C/O in the deep atmosphere
- > Internal structure



Why are Uranus and Neptune so different?

- M(Neptune) > M(Uranus) -> Why?
- Uranus tilted on the ecliptic -> Why?
- Same sizes and densities, but very different atmospheres
  - Neptune: Internal energy, strong vertical mixing…
  - -> different internal structures (convection inhibited in Uranus?)
  - A consequence of early history and migration?
- Possible tracers: Tropospheric CO, PH_3

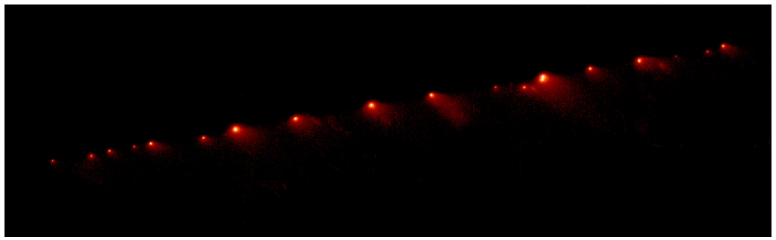
Key questions about the outer solar system formation and evolution (2)

What can we learn from the diversity of distant small bodies (satellites & asteroids)?

- Search for tiny atmospheres (H_2O, CO, HCN)
- Search for water envelopes around asteroids (cf Ceres)
- Elemental and isotopic ratios in Titan
- Origin of water in Saturn's system

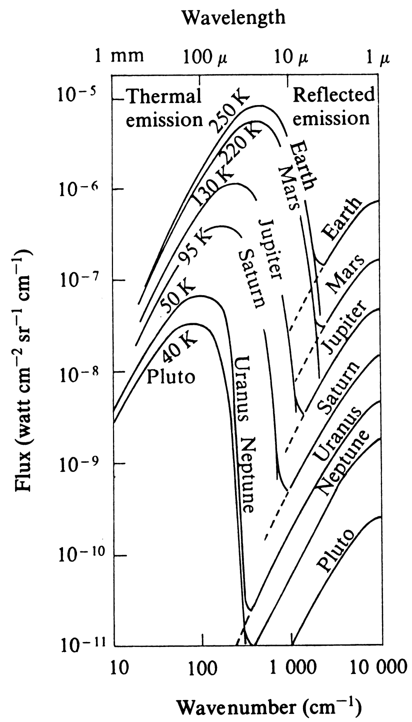
Can we characterize the oxygen flux in the outer solar system?

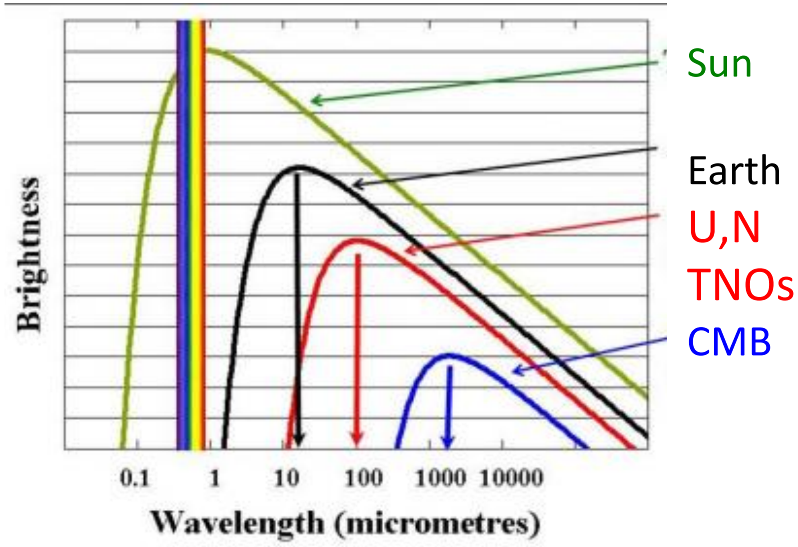
- Mapping of stratospheric H_2O in the giant planets
- Oxygen source: Icy Satellites? Comets? Meteoritic flux?



Thermal emission in the outer solar system is best observed by far IR/submm remote sensing

- **Outer solar-system objects are cold**
  - Giant planets: λ_{max} from 25 μm (Jupiter) to 60 μm (U, N)
  - Outer satellites: 30 μm (Galilean sat.) > 70 μm (Triton)
- **In situ exploration is limited to a few targets**
  - Uranus and Neptune were only explored by Voyager in the 1980s, no future mission planned
  - No planned mission toward Saturn system after Cassini
- **All strong molecular rotational transitions are found in the far IR/submm range**
- **Space is needed in 2 cases:**
  - Observation of molecules not observable from Earth (H_2O, O_2, O_3…)
  - Large wavelength coverage (rotation temperatures, spectral surveys)

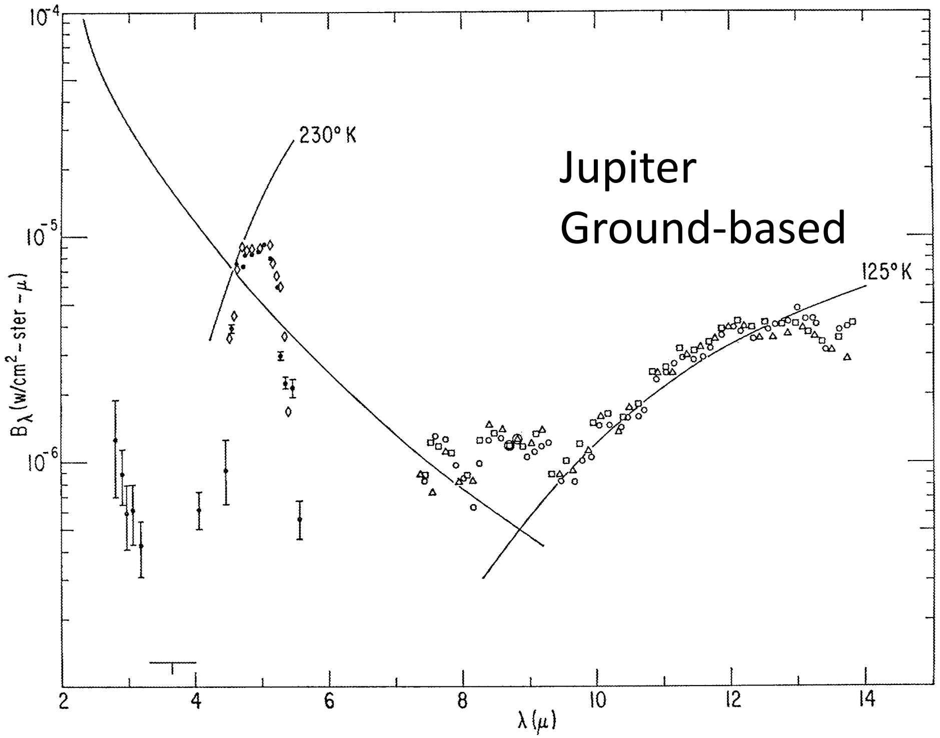


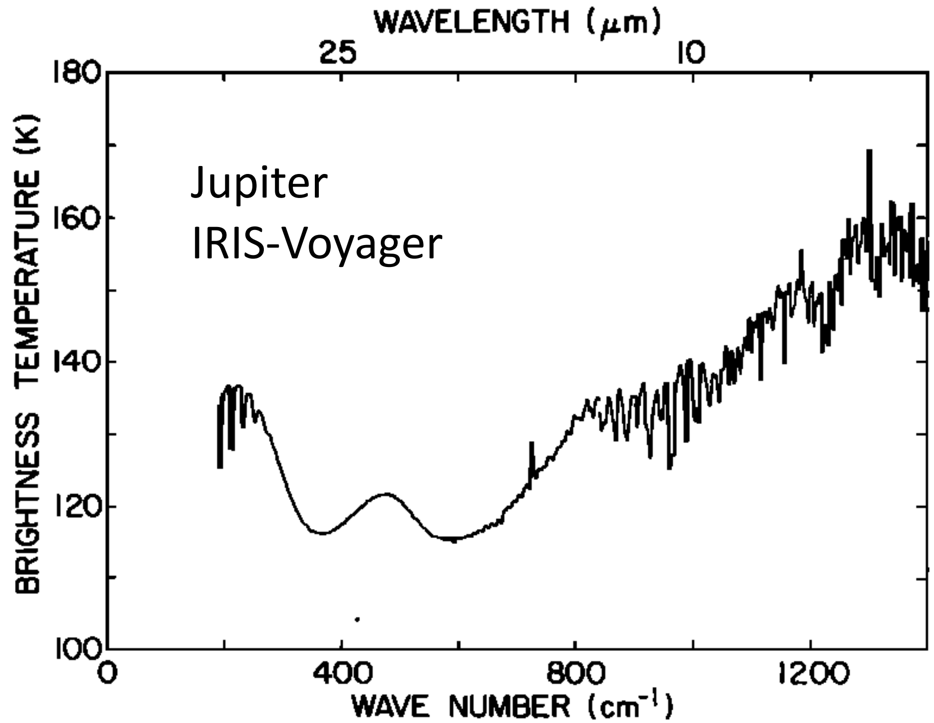


Herschel

A milestone in infrared planetary science

Evidence for an internal energy source in the giant planets
(except Uranus)





Gillett, 1969
T_B = 125 K

Hanel et al., 1981
T_B = 124.4 K

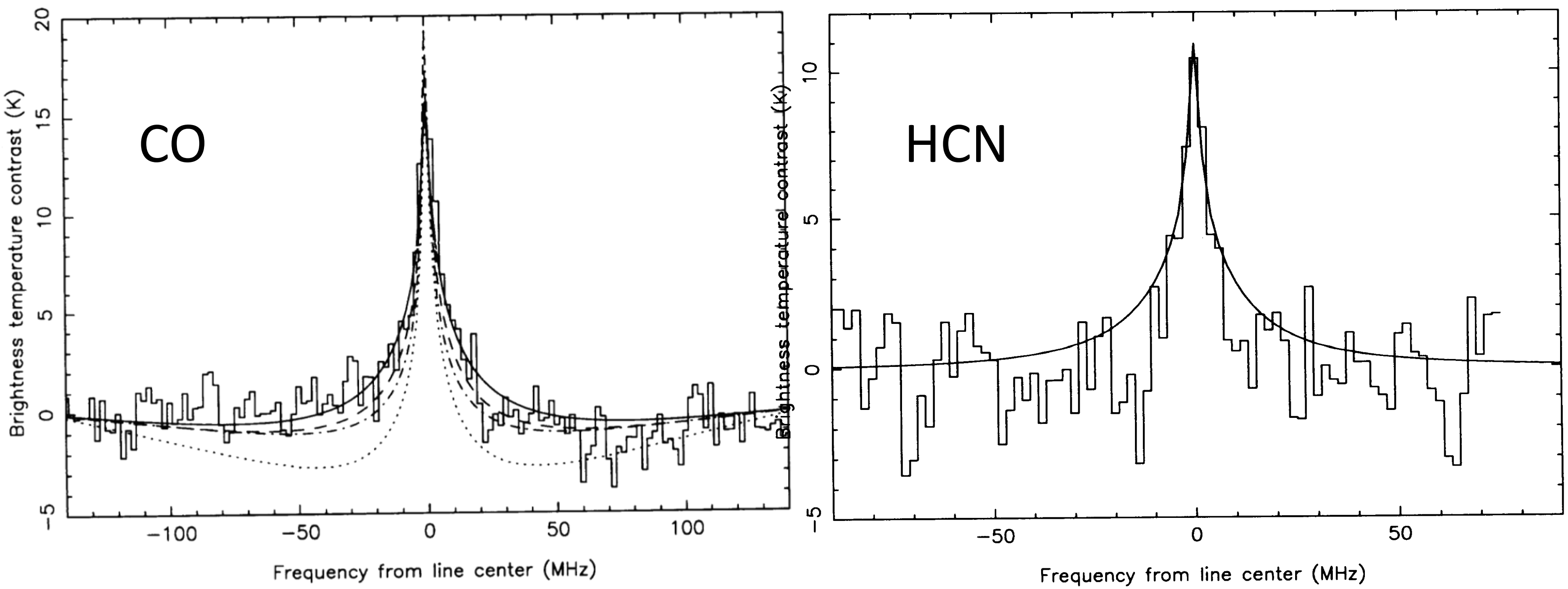
Jupiter: Evidence for an internal energy source, 1.7 times the absorbed solar energy (T_{eq} = 110 K)
Probable origin: Gravitational contraction

Planetary atmospheres: A milestone in the millimeter range (IRAM-30m)

CO and HCN in Neptune (1992)

-> evidence for disequilibrium processes in Neptune

-> evidence for differences in the atmospheres of Uranus and Neptune



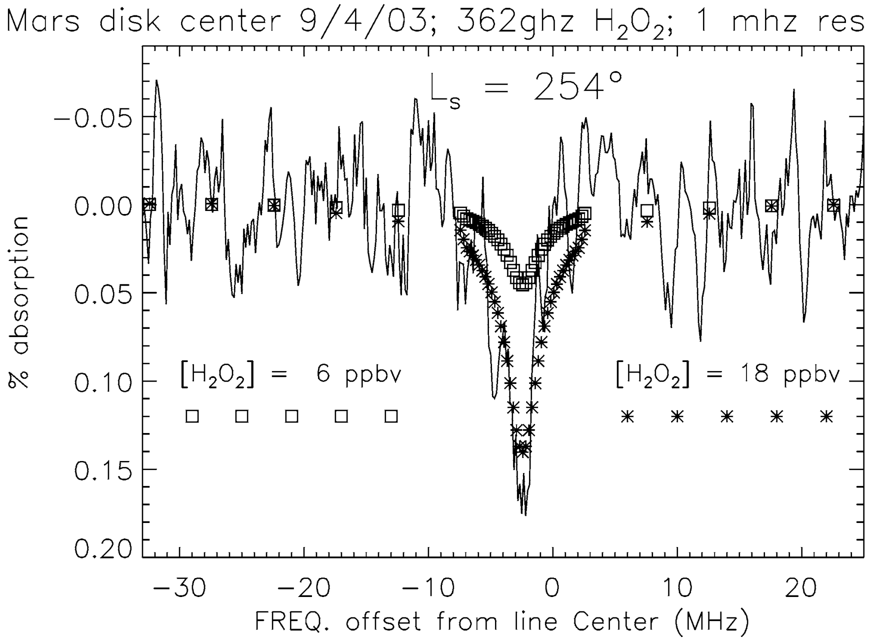
CO : 6 10^{-7} (expected: 10^{-9} from interior) in Neptune, < 4 10^{-8} in Uranus (internal/external?)

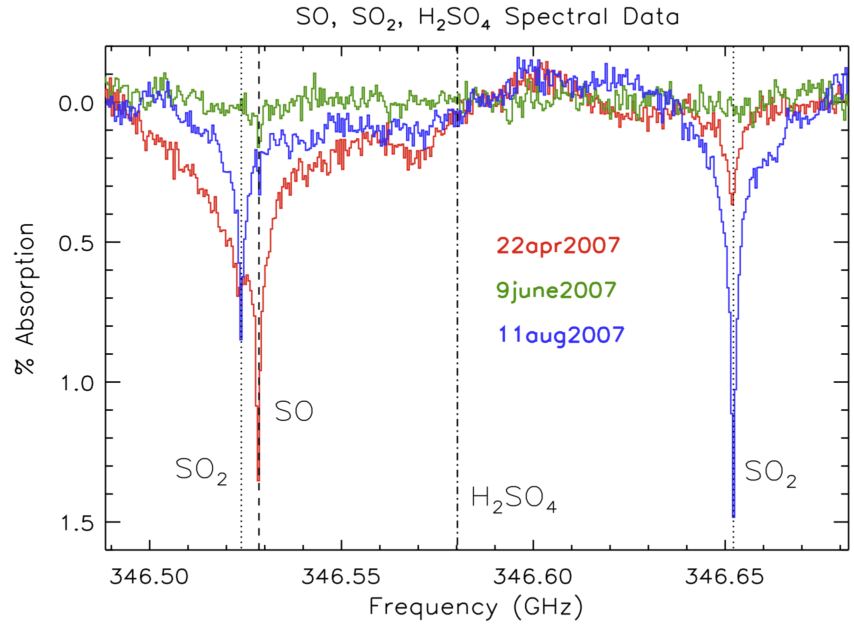
HCN: 3 10^{-10} in Neptune, < 8 10^{-10} in Uranus (external)

Rosenqvist et al. 1992

Planetary atmospheres:
Milestones in the submillimeter range (JCMT)

- H_2O_2 on Mars (2004)
- Mesospheric sufur species and HCl on Venus (2010, 2012)





H_2O_2 on Mars (Clancy et al. 2004)

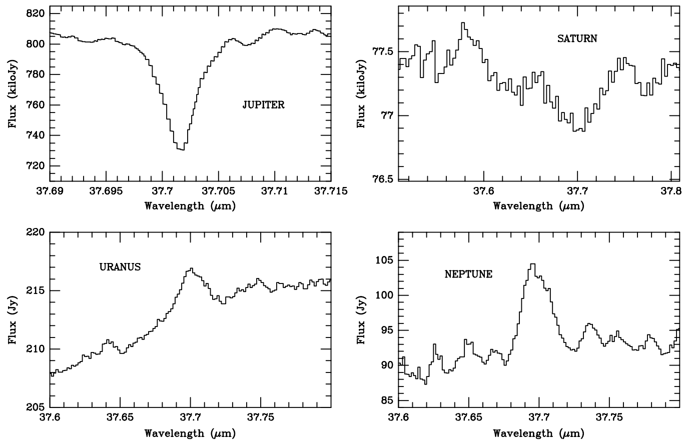
SO_2 & SO in the mesosphere of Venus
(Sandor et al. 2010, 2012)

ISO Highlights on Giant Planets

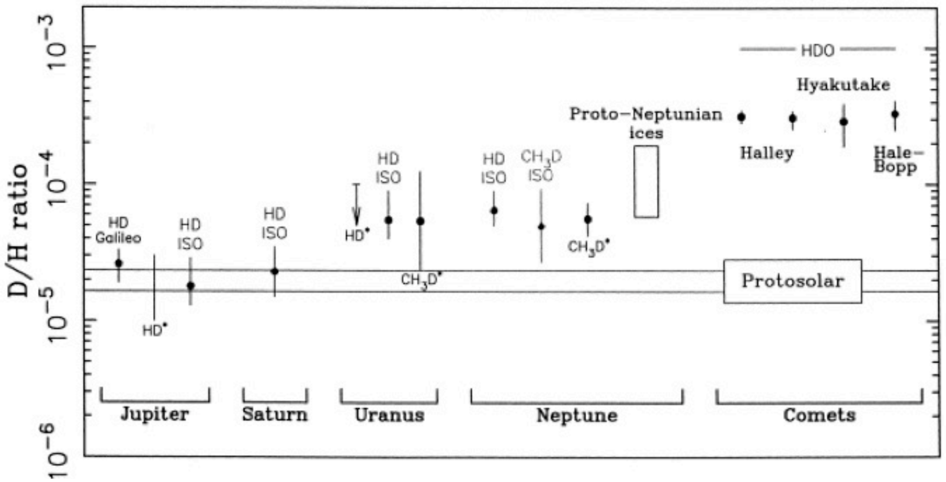
Origins: D/H from H_2

Deuterium enriched in icy giants

-> Support to nucleation model



Feuchtgruber et al. 1999; Lellouch et al. 2002



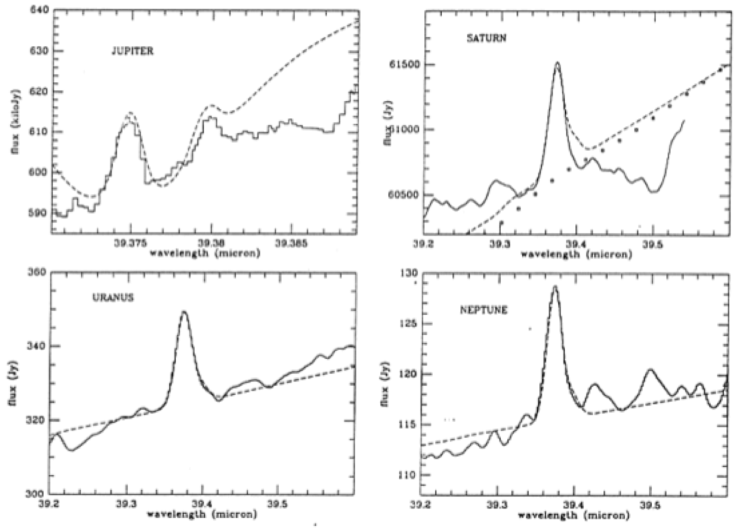
Encrenaz et al. 1999

External oxygen flux: source?

-Local source (satellites, rings)

-Interplanetary source

- flux of meteoroids
- comets (Jupiter: SL9?)



Feuchtgruber et al. 1997

Planetary & satellite atmospheres: Herschel Highlights

Giant planets

- D/H in Uranus and Neptune
- Stratospheric water in Jupiter, Saturn and Titan
- CO in Uranus (Cavalié et al. 2014)

Outer satellites

- Atmospheric composition of Titan

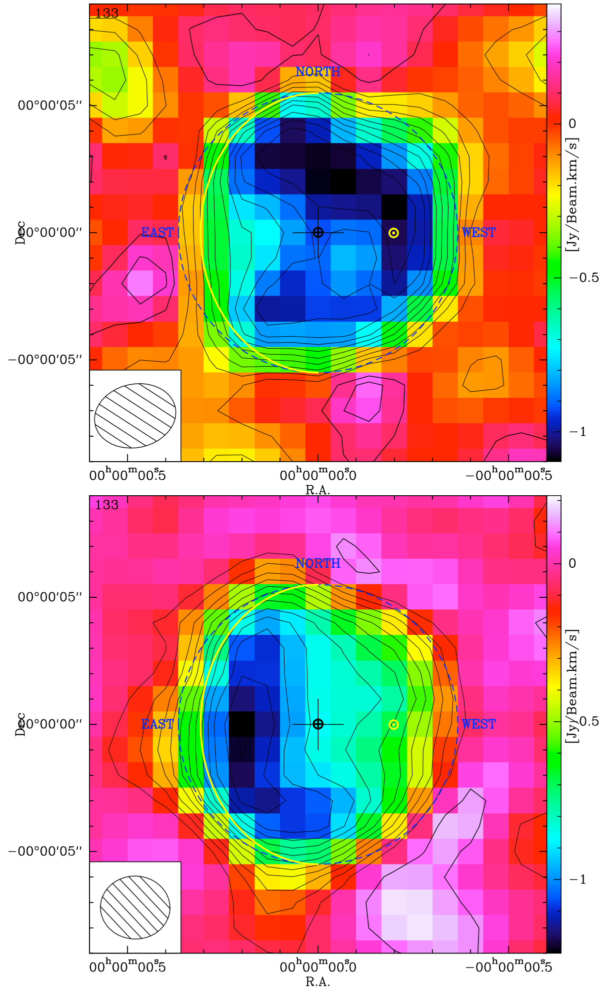
  (Moreno et al. 2011, 2012; Courtin et al. 2011
- Water torus of Enceladus (Hartogh + 2011)
- H_2O atmosphere around Ganymede and Callisto

Asteroids: Detection of H_2O around Ceres

Planetary atmospheres with ALMA

- **Main objectives**
  - Search for minor species
  - Dynamics & photochemistry
  - **Venus and Mars**
    - CO mapping: T(z) + winds
    - Venus: HDO, Sulfur & Chlorine species
    - Mars: HDO, H_2O_2
  - **Giant planets & Titan**
    - CO, HCN mapping: T(z) + winds
  - **Other outer satellites**
    - Io: volcanism (SO_2)
    - Enceladus: HCN
    - Future studies: CO, HCN (Gal. Sat)
- **What will not be done:**
  - H_2O, O_2, O_3, halides…
  - Broad spectral coverage

Venus, SO @ 346.5 GHz

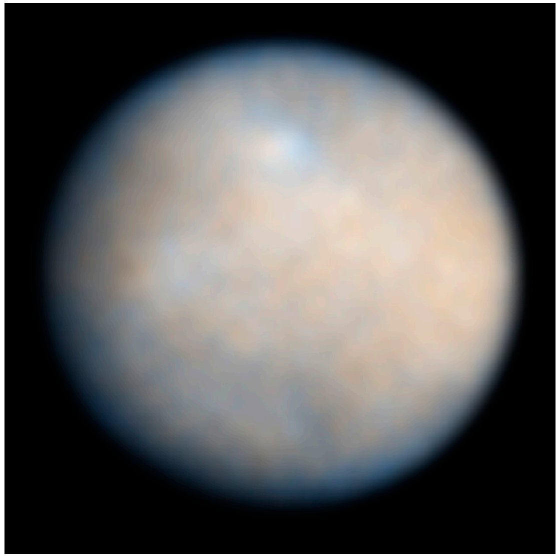


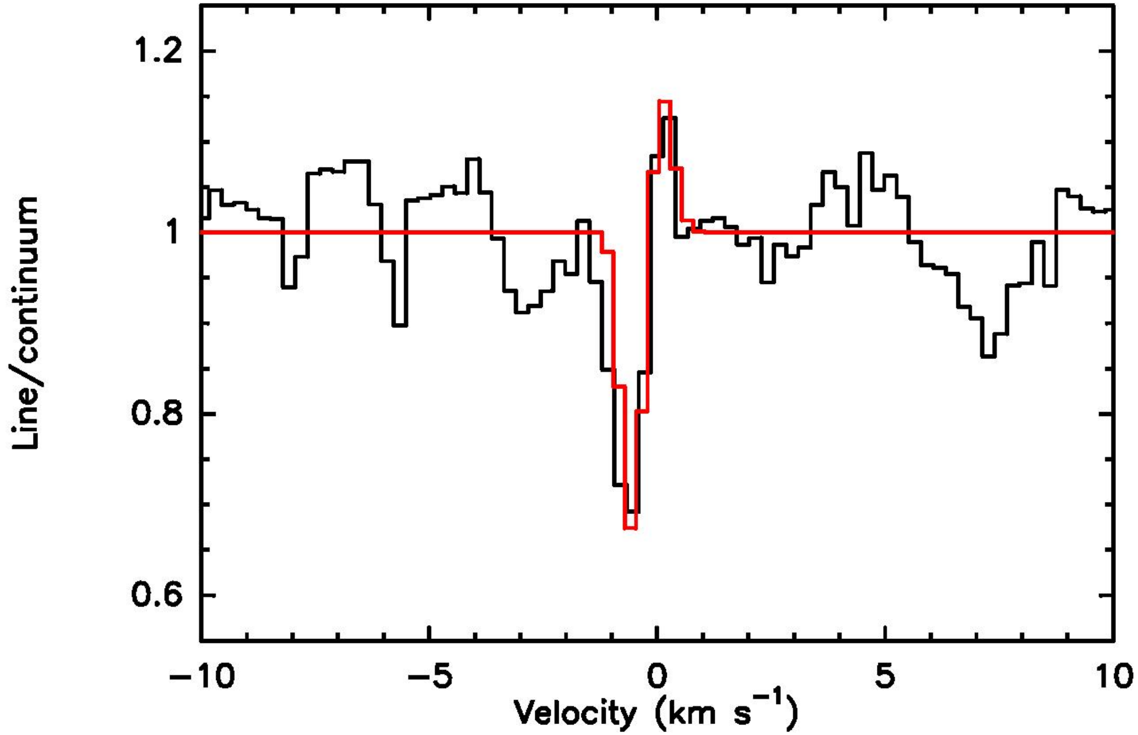
Nov. 14, 2011

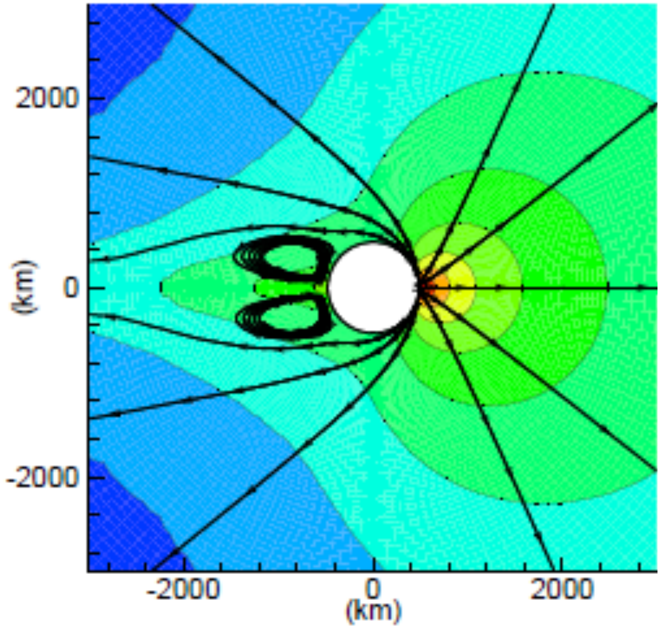
Nov. 15, 2011

Encrenaz et al. 2014

An unexpected discovery:
The detection of water vapor around Ceres (HIFI)







557 GHz H_2O line detected with HIFI in October 2012 and March 2013

Kueppers et al., 2014

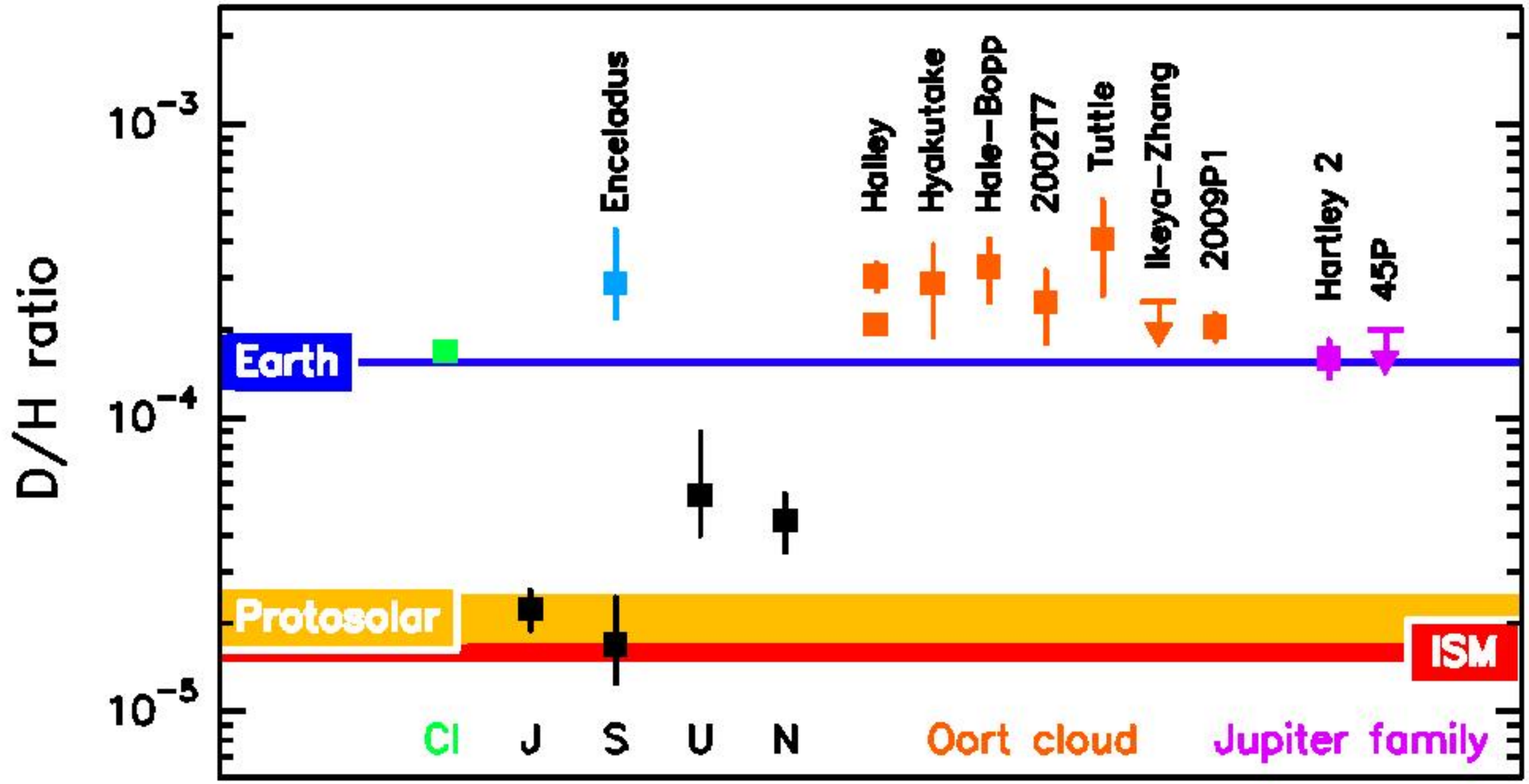
What is the frontier between asteroids and comets???

A water envelope around Ceres: What does it mean?

- Water-rich small bodies are expected to be found beyond the snow line
- The presence of water around Ceres might suggest that some icy bodies migrated inward
- Would also explain the presence of hydrated minerals at the surface of Ceres
- Exploring the water content of asteroids is important as a possible tracer of their migration
- Will also help to identify the origin of terrestrial water

What is the origin of terrestrial oceans?

A diagnostic: the D/H ratio in water



Lis et al. 2013

$[D/H]_E = 1/2 \times [D/H]_{Oort\text{-}cloud\text{-}comets}$

$[D/H]_E = [D/H]_{CC\text{-}Meteorites}$ but also $= [D/H]_{Kuiper\text{-}Belt\text{-}comets}$

-> Origin of oceans: D-type MBA or Kuiper Belt comets?

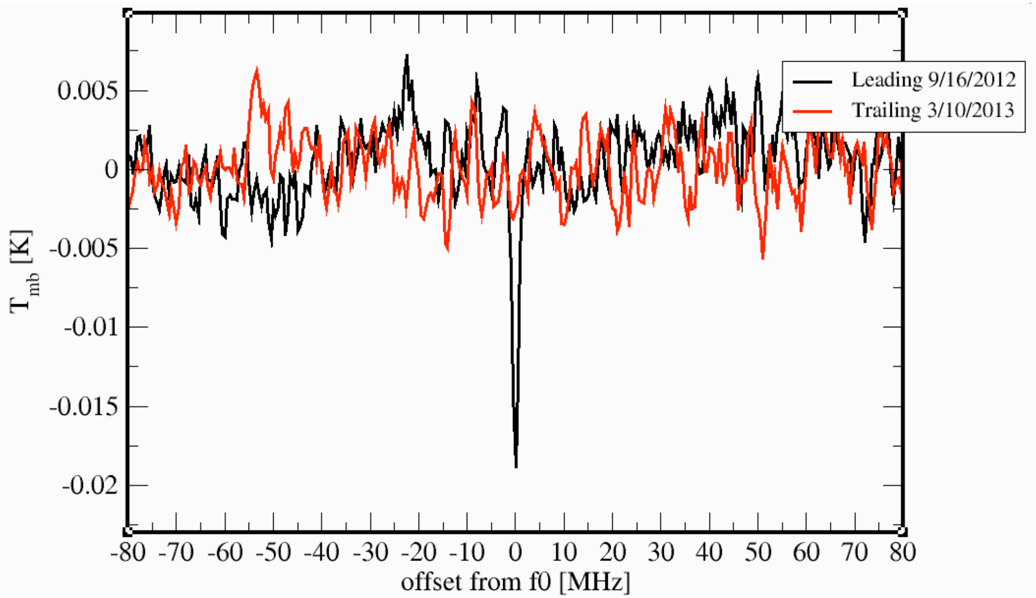
Water envelopes around small bodies: What to do next?

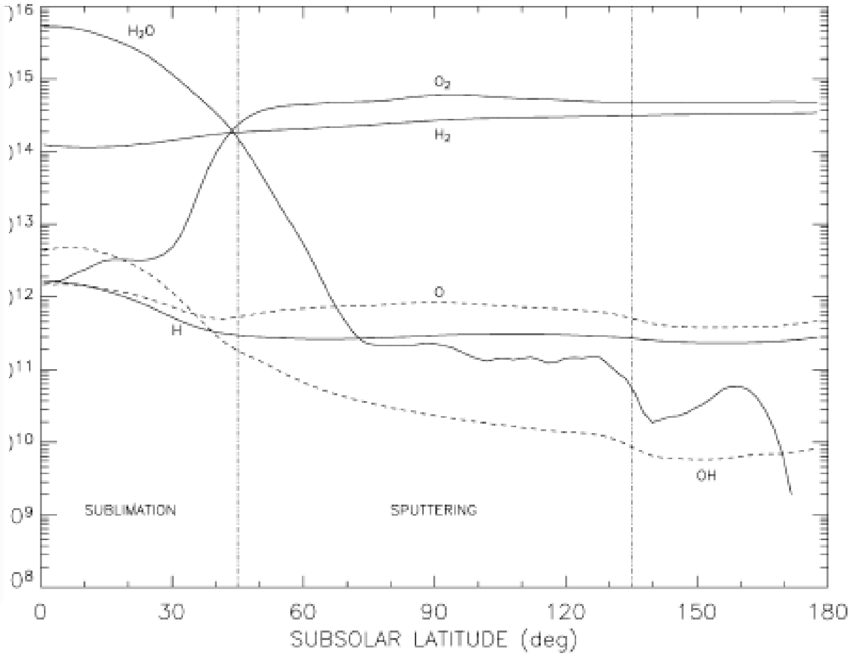
- Search for water envelopes around a variety of asteroids:
  - Outer main belt asteroids (possible origin of terrestrial water)
  - Centaurs near perihelion
  - Continuum flux: about 1 Jy for an MBA with 100 km diameter
- What is required?
  - Heterodyne spectroscopy
  - Size about 100 km -> gain of factor 100 in sensitivity vs Herschel/ HIFI (-> cooled telescope)
  - No need for spatial resolution
- Which instrument?
  - CALISTO, MMSO

Water envelopes around small bodies
Desired Measurement Capabilities

Parameter	Units	Value or Range
Wavelength range	μm	180 (1167 GHz)
Angular resolution	arcsec	2-3 arcsec
Spectral resolution, (λ/Δλ)	dimensionless	10^6
Continuum sensitivity	μJy	1000
Spectral line sensitivity	10^{-19} W m^{-2}	0.01
Instantaneous FoV	arcmin	5 x 5 arcsec
Number of target fields	dimensionless	
Field of Regard	sr	

Another surprise from Herschel/HIFI: Water vapor on Ganymede and Callisto (557 GHz)





H2O @ 557 GHz on Ganymede,
Sept. 2012 (HIFI)
P. Hartogh, Herschel Conference,
Oct. 2013

Distribution of H_2O and other species as a function of subsolar latitude in Ganymede's atmosphere
(M. L. Marconi, Icarus, 2007)

What to do next?
Mapping water envelopes of satellites & large asteroids

- **Objective:** Determine the distribution of water (trailing/leading sides on Ganymede, localized sources…)
- **What is required?**
  - Heterodyne spectroscopy @ 1167 GHz
  - Spatial resolution
- Ganymede is 1.3 arcsec in diameter → FOV: 0.6 arcsec (5 points over the disk)
- Fcont(G) = 26 Jy, in FOV: 1.4 Jy
- Line is seen in absorption (about 20%) – Expected signal: 0.3 Jy

-> Sensitivity: Factor 16 vs Herschel/HIFI

- Spatial resolution: 60 m baseline interferometer
- Which instrument? ESPRIT

Water mapping on Ganymede
Desired Measurement Capabilities

Parameter	Units	Value or Range
Wavelength range	μm	180 (1670 GHz)
Angular resolution	arcsec	0.6 arcsec
Spectral resolution, ($\lambda/\Delta\lambda$)	dimensionless	10^6
Continuum sensitivity	μJy	2000
Spectral line sensitivity	10^{-19} W m^{-2}	0.02
Instantaneous FoV	arcmin	2 x 2 arcsec
Number of target fields	dimensionless	
Field of Regard	sr	

Water mapping in Jupiter with Herschel (PACS/HIFI)

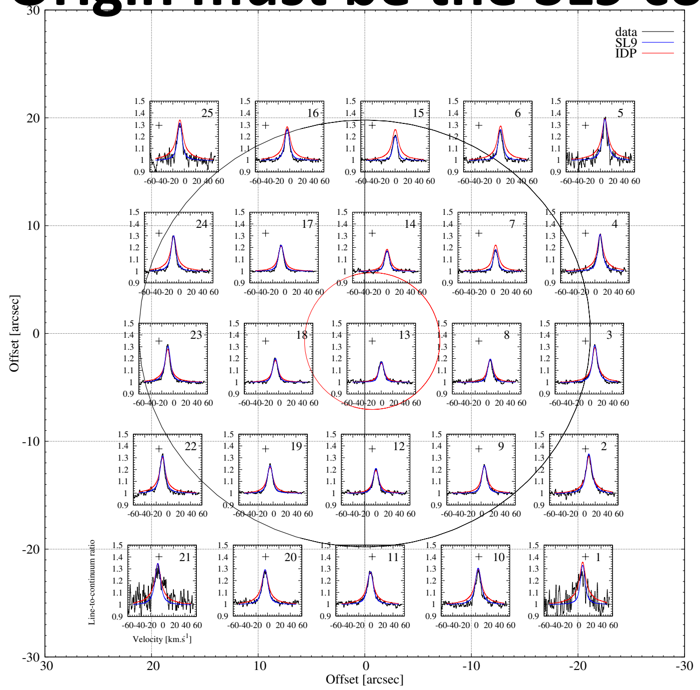
- H_2O in Jupiter (PACS/HIFI)

  Cavalié et al. 2013

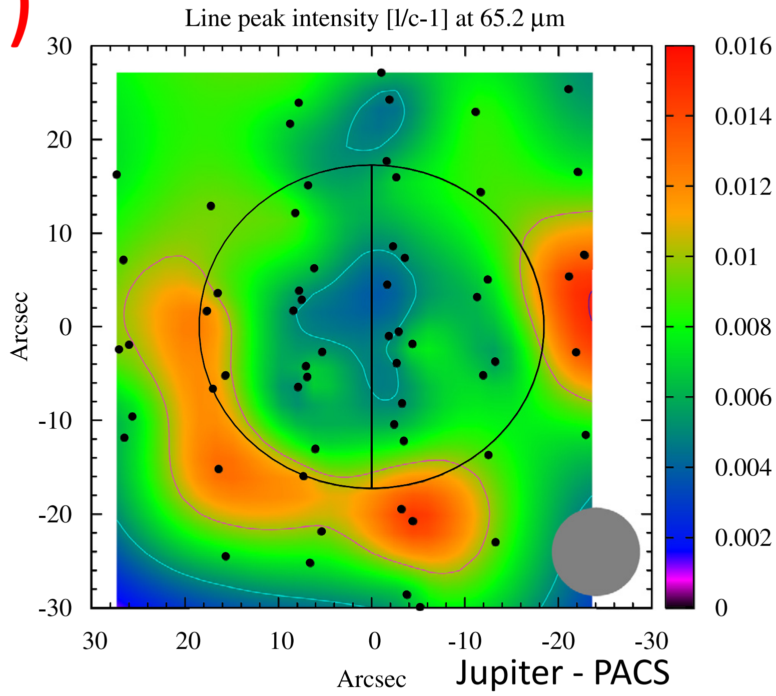
  – H_2O is above the 2 mbar level

  – Decreases from south to north latitudes

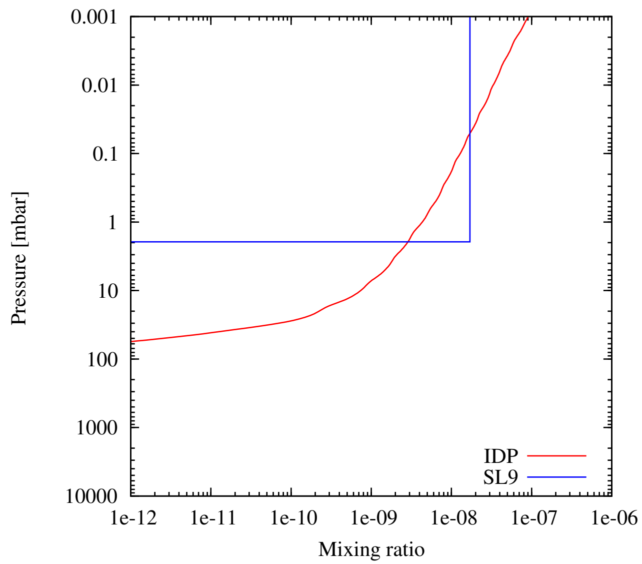
  – **> Origin must be the SL9 collision**

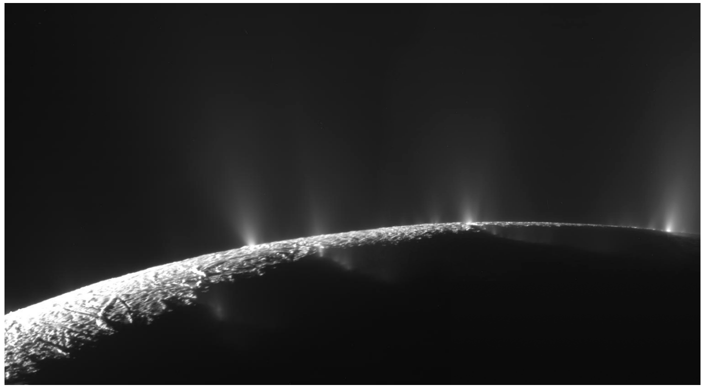


Jupiter-HIFI

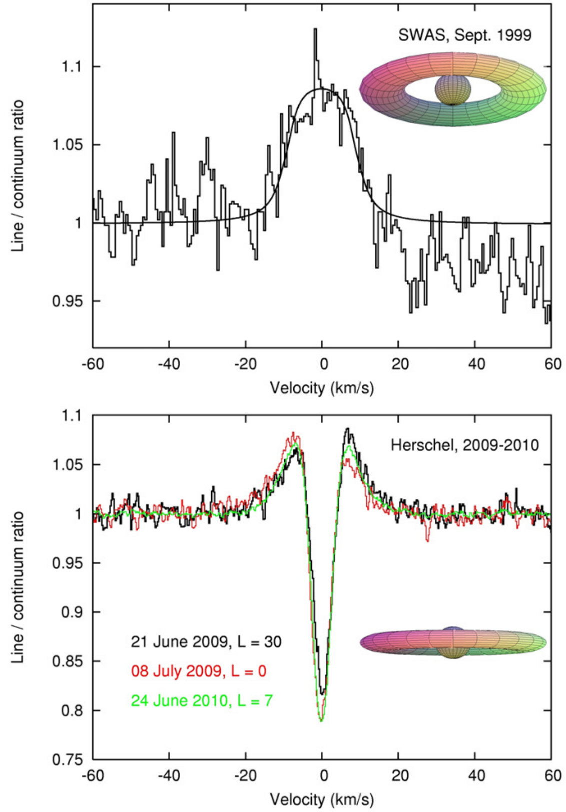


Jupiter - PACS





The origin of water in the system of Saturn



Hartogh et al. 2011

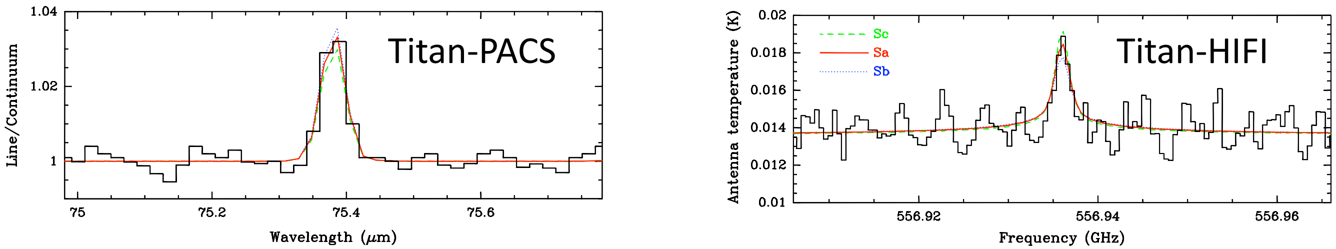
- Detection of the water torus generated by Enceladus (HIFI)

- Cryovolcanism on Enceladus has been reported by Cassini

- Using appropriate geometry, HIFI has detected the H_2O torus generated by Enceladus, in absorption in front of the H_2O emission of Saturn

- H_2O in Titan (PACS/HIFI) Moreno +13

- Oxygen flux is weaker than previously inferred from ISO
  - **> Enceladus cryovolcanim is sufficient to explain Saturn & Titan's external water**



Moreno et al. 2013

What to do next?
Water mapping on Uranus and Neptune

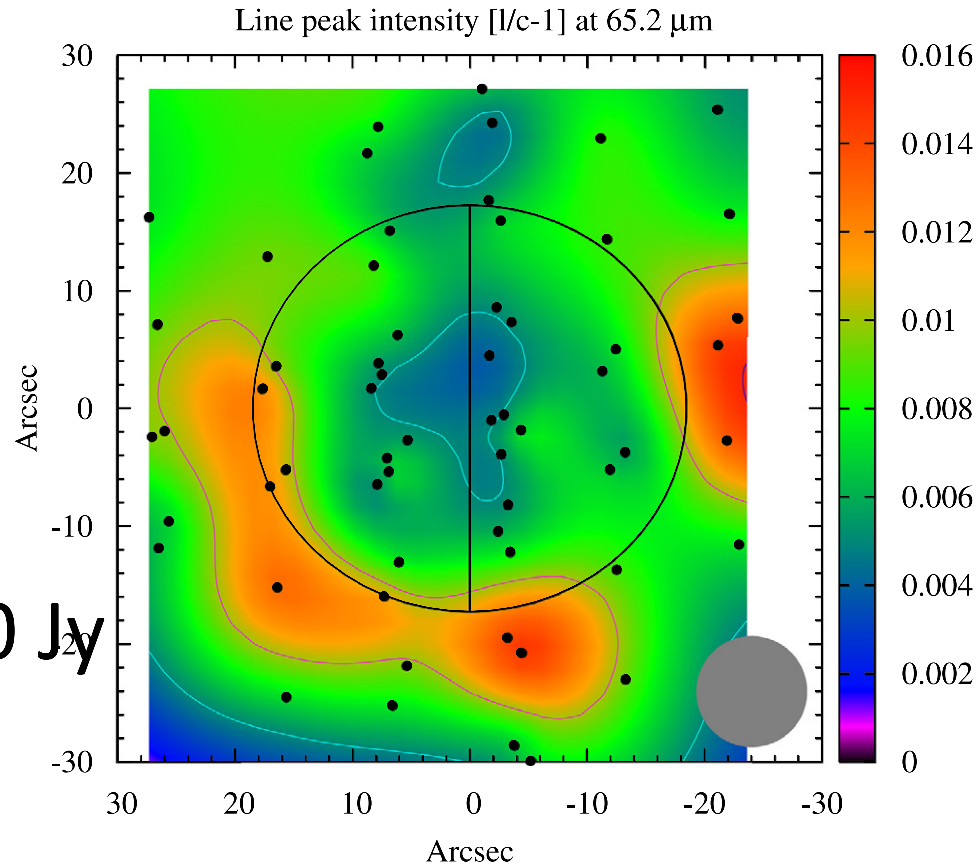
- Stratospheric water detected on Neptune with ISO, origin unknown
- Objective: Determine the origin of stratospheric water (comets, meteoroids) and its temporal evolution
- Two kinds of measurements needed:
  - Mapping @ 60 μm, R = 3000, FOV = 0.5 arcsec (PACS-type)
  - Mapping @ 1670 GHz, R = 10^6, FOV = 1 arcsec (HIFI-type)
- Flux in H_2O line is comparable to Jupiter for equal FOV (T_B = 150 K)

a. H_2O mapping of Neptune @ 60 μm

On Jupiter with PACS:

Beam = 9 arcsec

(Cavalié et al.2013 ->)



FOV equired on Neptune (2 arcsec): 0.5 arcsec

Fcont(Neptune)/beam = 10 Jy

Fline(N) = 20 10^{-19} W/m^2

->

Sensitivity: Factor 300 vs PACS/Herschel

Spatial resolution: 60 m baseline interferometer

Which instrument? SPIRIT (0.9 arcsec @ 60 μm)

Water mapping on Neptune @ 60 μm
Desired Measurement Capabilities

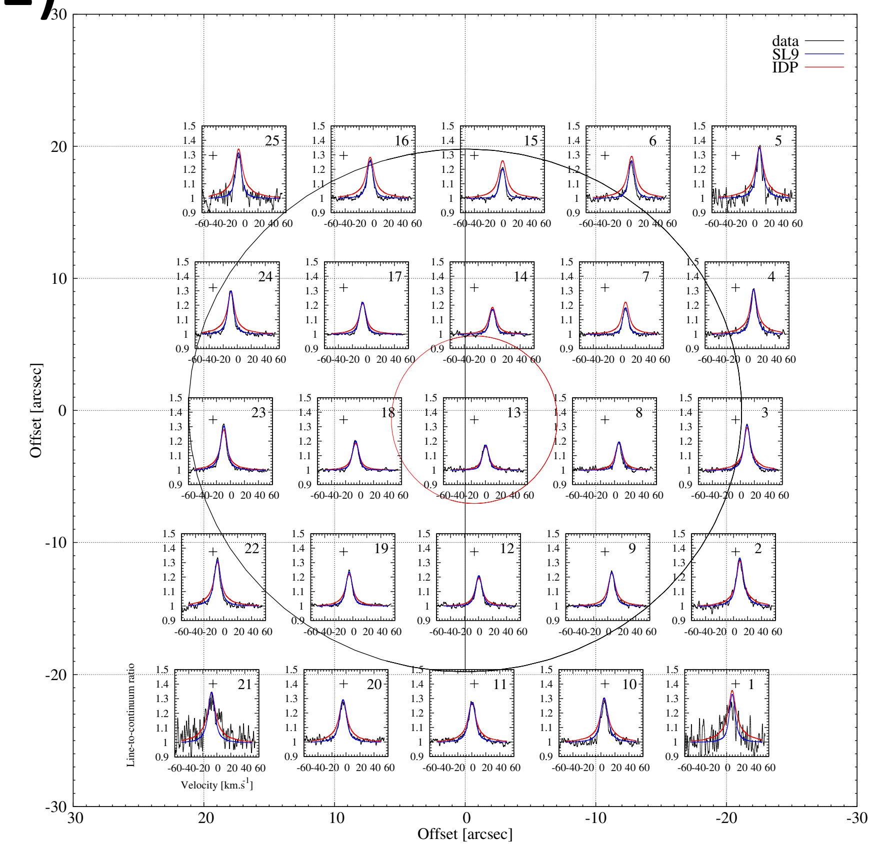
Parameter	Units	Value or Range
Wavelength range	μm	60
Angular resolution	arcsec	0.5 arcsec
Spectral resolution, ($\lambda/\Delta\lambda$)	dimensionless	3000
Continuum sensitivity	μJy	100
Spectral line sensitivity	10^{-19} W m^{-2}	0.2
Instantaneous FoV	arcmin	5 x 5 arcsec
Number of target fields	dimensionless	
Field of Regard	sr	

b. H_2O mapping of Neptune @ 1670 GHz

On Jupiter with HIFI (1670 GHz)

Beam = 13 arcsec

(Cavalié et al.2013 ->)



Required on Neptune

(2 arcsec):

Beam = 1 arcsec

Fcont(N) = 30 Jy

Fline = 60 10^{-19} W/m^2

-> Sensitivity: Factor 170 vs Herschel/HIFI

Spatial resolution: 40 m baseline interferometer

Which instrument? ESPRIT

Water mapping on Neptune @ 1670 GHz
Desired Measurement Capabilities
(Second priority)

Parameter	Units	Value or Range
Wavelength range	μm	180 (1670 GHz)
Angular resolution	arcsec	1 arcsec
Spectral resolution, (λ/Δλ)	dimensionless	10^6
Continuum sensitivity	μJy	3000
Spectral line sensitivity	10^{-19} W m^{-2}	0.2
Instantaneous FoV	arcmin	5 x 5 arcsec
Number of target fields	dimensionless	
Field of Regard	sr	

Conclusions
Killer apps in atmospheric sciences

- **Search for water envelopes around distant small bodies**
  - Heterodyne spectroscopy required
  - CALIPSO, MMSO
- **Water mapping on the brightest small bodies**
  - Het. Spectroscopy + high angular resolution required
  - ESPRIT
- **Water mapping on Uranus and Neptune**
  - High angular resolution required
  - Possible at 60 mm with R = 3000 (SPIRIT)
  - Possible at 1670 GHz with R = 10^6 (ESPRIT)
- **In all cases: synergy with ALMA** (CO, HCN,…)